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A PROPOSED METHOD FOR IMPROVING THE PASSBAND CHARACTERISTICS OF THE PERIODIC INTERFEROMETRIC MODULATOR

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REPORT
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A PROPOSED METHOD FOR IMPROVING THE PASSBAND CHARACTERISTICS OF THE PERIODIC INTERFEROMETRIC MODULATOR

I. INTRODUCTION

Earlier publications[1, 2, 3] have discussed the use of an interferometric modulator system for the selection and detection of far-infrared or submillimeter wavelength radiation in a desired frequency (or wavenumber) passband. This system consists of a periodic interferometric modulator which receives the incoming radiation and modulates it at several audio frequencies simultaneously, followed by a square-law radiation detector which detects the modulated radiation. The output of the radiation detector is fed to a tuned amplifier - synchronous detector which operates at one of the basic modulation frequencies present in the output of the interferometric modulator (and hence in the radiation detector's output).

The interferometric modulator consists of an optical system which divides the incoming radiation into two paths, one of which is $\gamma_{(t)}$ cm longer than the other path. When the radiation from these two paths is recombined, the total power fed into the radiation detector is dependent upon the path-length difference $\gamma_{(t)}$, which varies in a linear, periodic manner from 0 to γ_m and back to zero again once every $2T_m$ seconds in the manner shown in Fig. 1. The output of the modulator contains components modulated at the frequencies $f_n = (\gamma_m/T_m)\ \nu_n = n/2\,T_m$, where n is an interger, $\nu_n = n/2\gamma_m = n/2\,T_m v$ is the central wavenumber associated with the modulation frequency f_n, and $v = \gamma_m/T_m$ is the velocity of path length change. Thus, if $T_m = 1$ second these will be audio components at frequencies separated by 0.5 cps. If we could select only one of these audio components, say where n = v is a particular interger, and correlate it with a correctly-phased audio reference signal at the frequency $f_r = r/2\,T_m$, we would then find that the normalized d-c output of the correlator (caused by a normalized radiation input where the spectral density is $E_{(\nu)} = 1$) would have a wavenumber (frequency)-response characteristic given by:

$$B_{r(\nu)} = \frac{\sin\{2\pi\ \gamma_m\ (\nu - \nu_r)\}}{2\pi\ \gamma_m\ (\nu - \nu_r)} \tag{1}$$

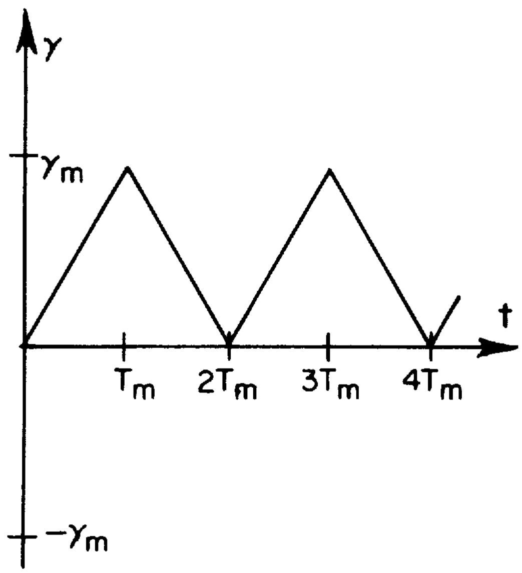

Fig. 1. Path length difference, γ, as a function of time.

where ν is the wavenumber of the incoming radiation. This response is shown in Fig. 2a. The correlator reference signal is derived from the optical-mechanical system which causes the variation in $\gamma_{(t)}$. It should be noted that since audio components at f_{r+1} and f_{r-1} are also present in the detector output, the correlator time constant must be much greater than 2 T_m (= 2 seconds for T_m = 1 second) if these components are to have a negligible effect upon the correlator output.

The resolution or bandwidth of the instrument is dependent upon the maximum path-length difference according to: $(\Delta\nu) = 1/\gamma_m$ where $(\Delta\nu)$ is the difference in frequency (wavenumber) between the first zeroes above and below the central maximum of $B_{r(\nu)}$. Thus by increasing γ_m the resolution or selectivity of the instrument can be increased. The relative resolution $\nu_r/(\Delta\nu)$ is given by

(2) $$\nu_r/(\Delta\nu) = \gamma_m \left(\frac{r}{2\,\gamma_m}\right) = \frac{r}{2} \qquad .$$

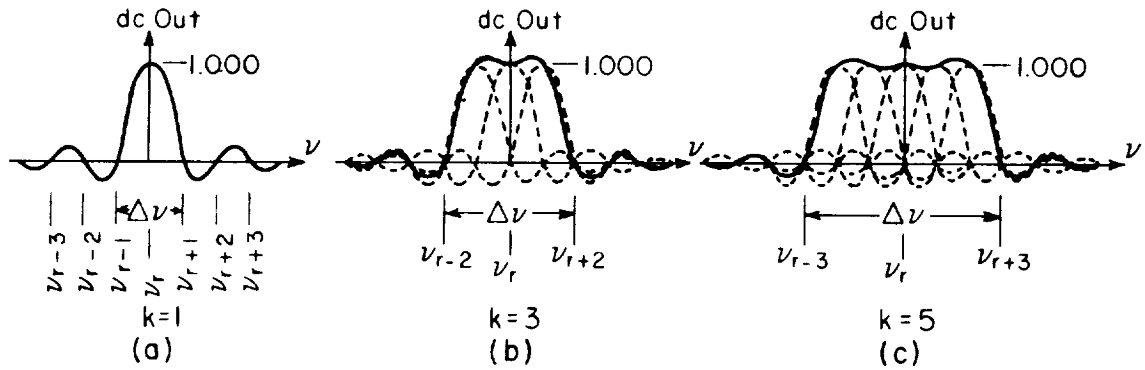

Fig. 2. Wavenumber (frequency) response of the interferometric modulator for one, three, and five reference signals.

If an instrument is designed with a response such as is given in Eq. (1) it is found that due to the "side lobes" of $B_{r(\nu)}$ there is a large contribution to the d-c output from radiation having wavenumbers outside the desired bandwidth $(\Delta\nu)$, while at the same time the shape of the response curve within $(\Delta\nu)$ is far from even approaching the rectangular shape which would be desirable. In the following sections it will be shown that it should be possible to modify the interferometric modulator to give a response function which can be made to approach a rectangular function within $(\Delta\nu)$ and in which the contribution from radiation with wavenumbers outside $(\Delta\nu)$ can be reduced to a very low level.

For the purpose of illustration we shall postulate a system wherein $f_r = 13$ cps, and $T_m = 1$ second. This means that $r = 26$ and that $\gamma_m = r/2\ \nu_r$ where ν_r is the central wavenumber to which the instrument is tuned. The relative resolution $\nu_r/(\Delta\nu) = r/2$ will be $26/2 = 13$. In the modified system we will again let $f_r = 13$ cps and $\nu_r/(\Delta\nu) = 13$.

II. IMPROVEMENT OF THE RESPONSE FUNCTION

In the analysis of the original system[1] it was assumed that only one reference frequency existed, and that when this was correlated with the output of the radiation detector only the audio-frequency component associated with $n = r$ produced any appreciable d-c output. This gave a response function as shown in Eq. (1) and Fig. 2a. In our example the reference frequency was $f_{n=26} = 13.0$ cps. However, these are also audio components at $f_{n=25} = 12.5$ and $f_{n=27} = 13.5$ cps in the output of the radiation detector. If we now also supply a correctly phased reference signal at each of these frequencies and add them to the original 13.0-cps reference signal, then when the output of the radiation detector is correlated with the total reference signal we will obtain essentially the sum of three response functions of the form shown in Fig. 2a where one function is centered at ν_r, one at ν_{r+1}, and the third at ν_{r-1}. The total result will be of the form shown in Fig. 2b. It can be seen that the form of the response is much improved over that of Fig. 2a. However, the bandwidth is now twice what it was in the original system, and if k reference signals had been used it would have been $\left((k-1)/2 + 1\right) = (k+1)/2$ times as large as the original bandwidth. This is really not a serious problem, though, since if the bandwidth of each individual peak is reduced by the factor $(k + 1)/2$, the total bandwidth of the system will remain the same. This can be done by increasing γ_m and T_m. In the case of three reference signals, T_m is increased from one second to two seconds and the new maximum path length difference is $\gamma_m' = 2\gamma_m$. This means that $r' = 52$, and $f_r' = 13.0$ cps, $f'_{r+1} = 13.25$ cps, and $f'_{r-1} = 12.75$ cps must be the reference frequencies. Instead of the time constant, τ, of the integrator circuit being much larger than 2 seconds, it must now be much larger than 4 seconds. in order to ensure no interaction between a reference signal at f_n and a signal component at f_{n+1}. However, since τ is usually made quite large anyhow to reduce the effects of detector noise, this is of little practical consequence.

Table I gives some consequences of using k reference signals. The information in the last column represents the ratio of the d-c output due to uniform radiation in the passband for k reference signals to the d-c output for one reference signal.

TABLE I
VARIATION OF RESPONSE FUNCTION WITH k

k	d-c output due to radiation at wavenumbers in main peak (A)	d-c output due to radiation at wavenumbers in side lobes (B)	percentage side lobes are of main peak (100 × B/A)	ratio of main peak output for k reference signals to main peak output for k = 1 (A/3.7038)
1	3.7038	-0.5622	15.18	1.0000
3	4.9449	-0.2325	4.70	1.3351
5	5.3807	-0.1447	2.69	1.4528
7	5.6026	-0.1048	1.87	1.5127
9	5.7370	-0.0821	1.43	1.5489
11	5.8270	-0.0674	1.16	1.5732
13	5.8916	-0.0572	0.97	1.5907
15	5.9429	-0.0524	0.88	1.6045
17	5.9804	-0.0463	0.77	1.6147
19	6.0105	-0.0415	0.69	1.6228
21	6.0351	-0.0375	-.62	1.6294
23	6.0557	-0.0343	0.56	1.6350
25	6.0731	-0.0316	0.52	1.6396

As may be seen from Table I, these would be little advantage in working with more than three to seven reference signals; the small advantage gained in reducing the ratio of side lobes to main peak by the use of a greater number of reference signals usually would not justify the added complexity. The data in Table I were obtained from the relations:

(3) $$\text{main peak d-c output} = A = \frac{4}{(k+1)} \sum_{n=1}^{k} \mathrm{Si}(n\pi)$$

(4) $$\text{lobe d-c output} = B = \frac{2\pi\ k}{(k+1)} - A$$

where

(5) $$S_{i(x)} = \int_{o}^{x} \frac{\sin u}{u} \, du \quad .$$

The top of the response function will have a certain amount of variation within the passband. This is illustrated in Fig. 3 for the cases k = 3 and k = 5.

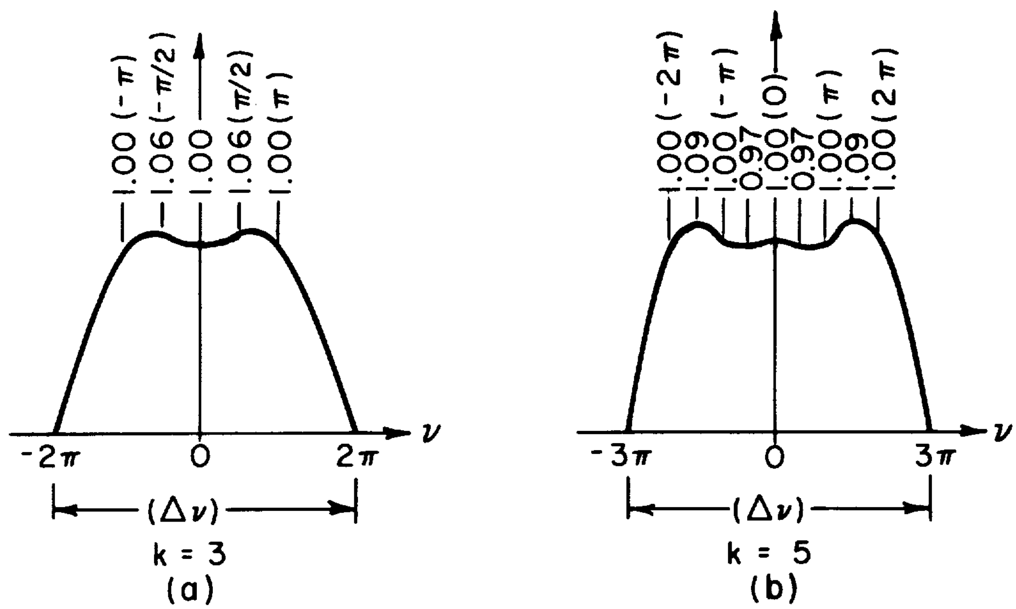

Fig. 3. Response function showing the "ripple" which occurs within the passband (Δν), the latter being the same in both cases.

III. NOISE LEVEL EFFECTS OF MODIFIED SYSTEM

In the case of the original system[1] it was shown that the equivalent noise input (in terms of rms noise fluctuations in the input power) observed in the correlator output was proportional to $1/\tau$, where τ was the correlator time constant. In the proposed new system there will be as many noise contributions as there are reference signals used. Thus, if we assume that the noise is such that there is no correlation between noise voltages occurring at different frequencies, then the total rms noise fluctuations in the new system will be $\sqrt{k}$ times that in the original system, assuming the same correlator time constant in both cases.

At the same time, γ_m has been increased by the factor $(k + 1)/2$, which causes the signal strength of one audio frequency component in the radiation detector output of the new system to be $2/(k + 1)$ that of the one of the components in the old system. There will be k such contributions to the d-c output, and we find that for a uniform input spectrum in the region of interest, the ratio of the total d-c output of the new system compared to that of the original system is $2k/(k + 1)$. Thus, the ratio of d-c signal to rms noise fluctuations for the new system is

$$\frac{2k}{(k+1)} \cdot \frac{1}{\sqrt{k}} = \frac{2\sqrt{k}}{(k+1)} \tag{6}$$

times that of the old system.

In order to achieve the same noise-equivalent power sensitivity with the new system as with the old, it is necessary to increase the correlator integration time by the factor $R = (k + 1)/2\sqrt{k}$, where R is tabulated versus k in Table II.

TABLE II
INTEGRATION TIME-INCREASE FACTOR

k	1	3	5	7	9	11	13	15	17	19	21	23	25
R	1	1.155	1.341	1.513	1.667	1.81	1.94	2.06	2.18	2.29	2.40	2.50	2.60

IV. MULTIPLE-CORRELATION TECHNIQUES

There are two basic means of correlating an input signal with a sine-wave reference signal. One method involves simply multiplying the two signals together and passing the output of the multiplier through a low-pass filter of time constant τ. This is shown in Fig. 4. However, it is difficult to build a multiplier which remains linear over a wide dynamic range of input signals. To surmount this problem the chopper-type correlator has found widespread use. In this system the input

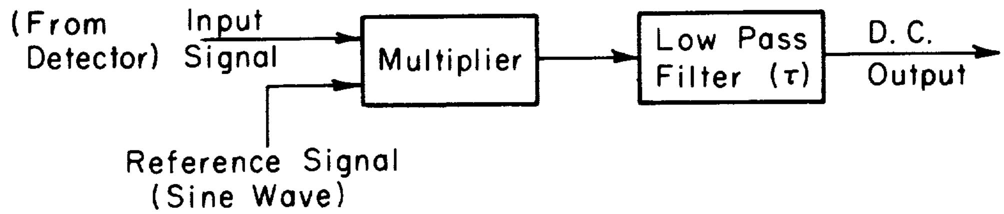

Fig. 4. Single-channel multiplier-type correlator.

signal is "multiplied" with a square wave whose first-harmonic component is at the same frequency and in phase with the desired sine-wave reference signal. The "multiplication" takes place in either a cam-operated switch, an electromechanical chopper, or an electronic chopping circuit. In order to eliminate any interaction between the input signal and the higher-order (i.e., 3^{rd}, 5^{th}, 7^{th}, etc.) harmonics of the basic chopping frequency, the input signal is first passed through a low-pass filter whose cut-off point lies between the first and third harmonics of the chopping frequency. Figure 5 shows such a chopper-correlator system.

In the case where several reference signals must be correlated with a single input signal, the system of Fig. 6 could be used. In this system all of the reference signals are added together and their sum is multiplied with the input signal. However, this circuit would suffer from the effects of multiplier nonlinearity. Another system, based on the chopper-correlator, is shown in Fig. 7. It can be seen that this is just an extension of the one-channel chopper type system to three channels. The input filter has its cut-off frequency somewhere between the first harmonic of the highest-frequency reference signal and the third harmonic of the lowest-frequency reference signal.

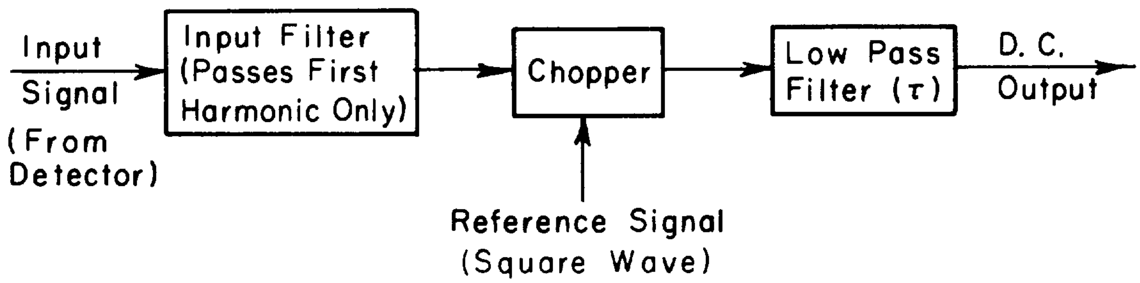

Fig. 5. Single-channel chopper-type correlator.

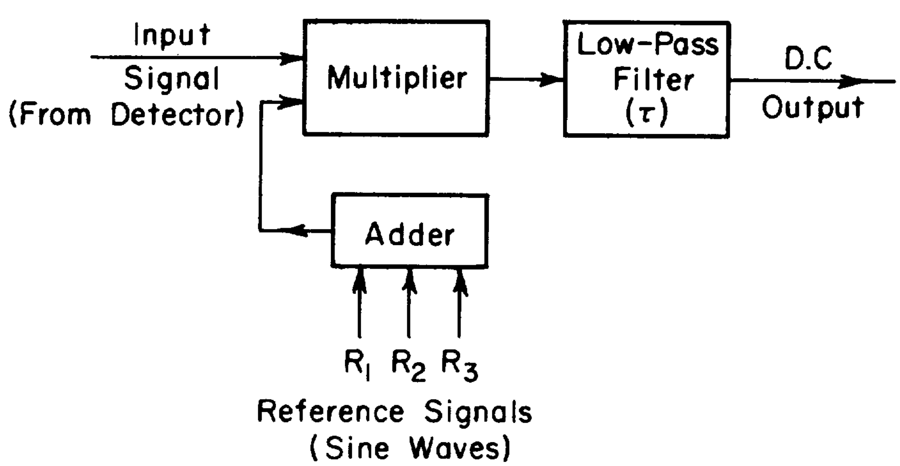

Fig. 6. Three-channel (k = 3) multiplier-type correlator.

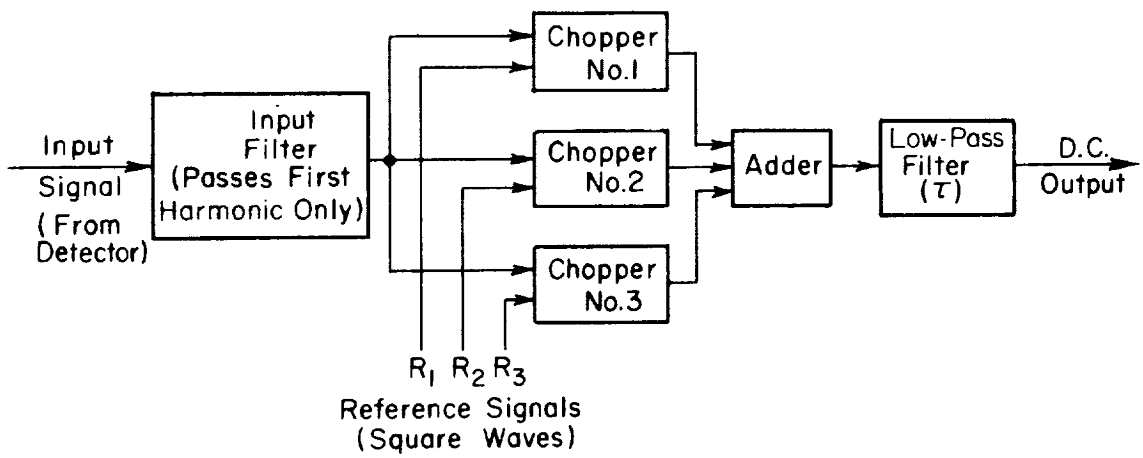

Fig. 7. Three-channel (k = 3) chopper-type correlator.

V. A PRACTICAL MULTIPLE-CORRELATION SYSTEM FOR USE WITH THE INTERFEROMETRIC MODULATOR

In the periodic interferometric modulator it would be desirable to have γ increase from 0 to γ_m and back to zero again with a perfectly linear motion such as shown in Fig. 8a. However, because of the inertia of the drive mechanism and the moving optical parts, the actual motion may be more nearly as shown in Fig. 8b. The finite turn-around time at zero and γ_m will cause some distortion to be present. One way of getting around this problem is to use a path-length-difference function such as is shown in Fig. 8c. In this case the turn-around occurs outside the time interval T_m, and during this time a blanking pulse is supplied to the electronic circuitry so that essentially there will be no correlation taking place during this turn-around time interval. The reference signal is also discontinuous during this blanking period.

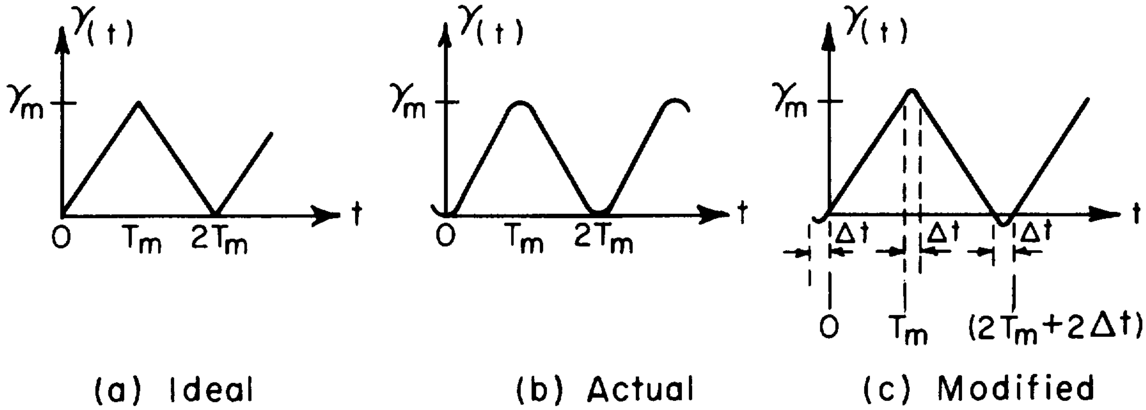

Fig. 8. Path-length difference functions.

Thus, any signal arriving during the turn-around time Δt will have no effect upon the output.* Figure 9 shows how such a system may be constructed. The blanking signal and the three reference signals (square waves) are derived from three photoelectric cells each of which scans a piece of film which is moved between it and a light source. The desired chopping characteristic has been placed on the film by photographic means.

* Modifying the modulating action and the reference signal in this manner causes sidebands to appear on each of the audio components and its corresponding reference signal. The chopper-correlator effectively correlates the main component (i.e., the "carrier") and the sideband components at the same time. Therefore, no special problems are introduced by modifying the modulator action in this manner.

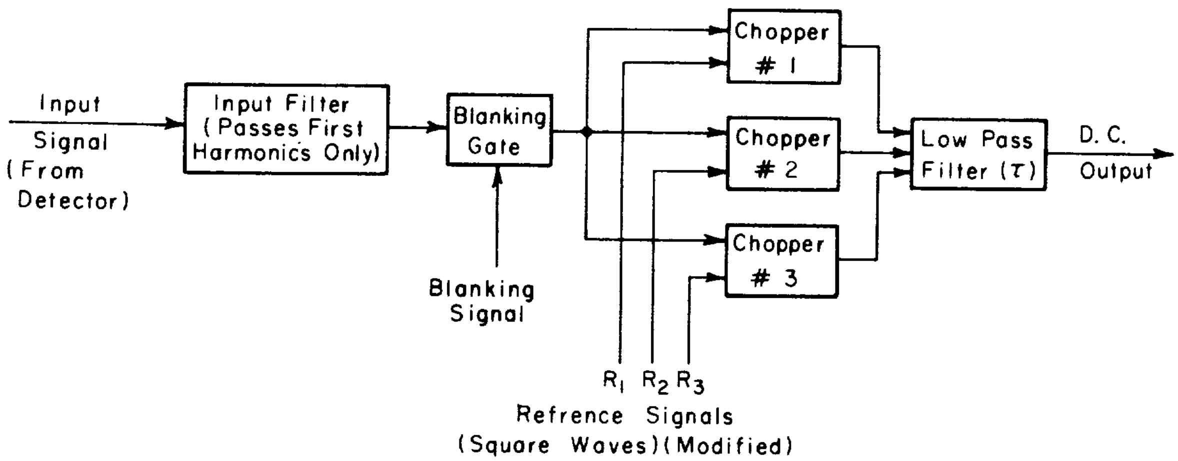

Fig. 9. Modified three-channel chopper-type correlator system.

VI. SUMMARY AND CONCLUSIONS

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In the preceding it has been shown that the response curve of an interferometric modulator may be improved by using multiple-correlation techniques, and that while the sensitivity of system using such a modification of the interferometric modulator will suffer to a small extent, this loss of sensitivity can be made up by making the correlator time constant, τ, slightly longer. A practical system for employing this multiple-correlation technique has also been proposed.

VII. REFERENCES

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